Absolute Calibration of Condenser Transmitters

By L. J. SIVIAN

Several methods have been used or proposed for the calibration of the Wente condenser transmitter. The methods falling under the two classifications conveniently designated "constant pressure" or "pressure" calibration and "constant field" or "field" calibration are most useful and amenable to measurement. Which of these two calibrations is more significant depends on the particular use made of the transmitter. In the following pages the methods now used or proposed are reviewed and the advantages or disadvantages of each from the standpoint of transmitter application are discussed.

IN the original design of the Wente[1] transmitter the effective diaphragm resonance was well above 10,000 c.p.s. The new design (Western Electric No. 394-Type), developed by Wente, has an effective resonance at approximately 5,000 c.p.s. It is about ten times more sensitive (on a voltage-pressure basis), and more immune from effects of humidity and of barometric changes. The important external dimensions of the instrument are shown in Fig. 1*A*.

The response of the transmitter is defined as the ratio of the electromotive force generated to the acoustic pressure acting on the trans-

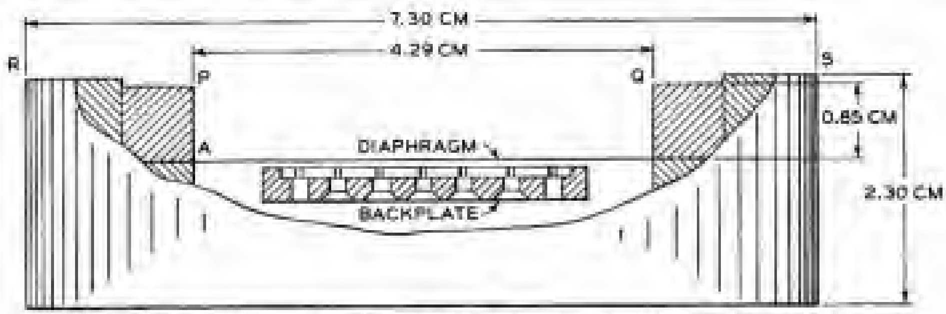

Fig. 1*A*—Contour dimensions of No. 394-type condenser transmitter.

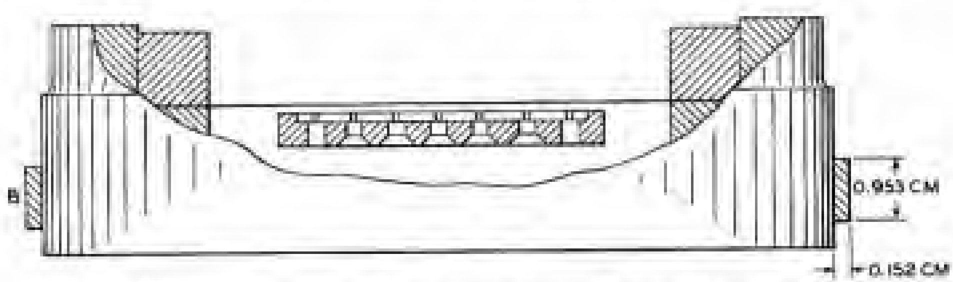

Fig. 1*B*—Contour dimensions of condenser transmitter used for field calibration.

[1] See bibliography.

mitter. That ratio $[R(f) = e/p]$, as a function of frequency, gives the calibration. Where and how is the acoustic pressure to be measured? This can be done in any one of a number of ways, all of which in general lead to different calibrations. The two calibrations most useful and amenable to measurement are when the pressure is uniform over the diaphragm and measured at the diaphragm and when the pressure is the pressure in a progressive plane wave, undistorted by the transmitter or any other obstacles; when the electromotive force is measured the distortion of the sound field must be due to the transmitter alone.

It is convenient to designate the former as "constant pressure" or "pressure" calibration, the latter as the "constant field" or "field" calibration. In general the field calibration will depend on the angle of wave incidence. Incidence normal to the diaphragm gives the "normal field" calibration. Where no confusion can arise, "field" calibration will be used to imply normal incidence. The pressure and field calibrations tend to coincide when the transmitter dimensions are small compared to the sound wave-length and when there are no appreciable impedances between the diaphragm and the sound field in front of it. Neither condition obtains for the No. 394-Type Transmitter, except at very low frequencies.

Which of the two calibrations—"pressure" or "field"—is more significant depends on the particular use made of the transmitter. Thus in the receiver testing machine, where the sound is substantially uniform throughout a small chamber closed by the transmitter diaphragm and by the receiver under test, the pressure calibration is important. When the transmitter is used to pick up sound in the open air at a distance from the source, the field calibration applies. For other cases, neither calibration is directly applicable, this being discussed at the end of the paper.

Constant Pressure Calibrations

For the several methods available for constant pressure calibration, the pressure may be applied either acoustically or electrically. In the acoustical group are the following methods:

1. Thermophone.[2]
2. Pistonphone.[1, 2]
3. Resonating tube.[3]
4. Compensation methods.
    a. Electrodynamic compensation for acoustic pressure.[4]
    b. Electrostatic compensation for acoustic pressure.[5]
5. Membranephone.

In the electrical group for pressure calibration are the following methods:

6. The back electrode (backplate) serving as the driving electrode.[5, 6]
7. An auxiliary third electrode driving the diaphragm.

All but two of the above methods have been described in detail in the articles to which references have been given so that only brief descriptions of the methods are given in the following paragraphs.

1. *Thermophone.*—The alternating pressure generated in the chamber of which diaphragm D (see Fig. 2) is one wall, is computed from the physical constants of the thermophone T, and of the gas (hydrogen) filling the chamber. A computation similar to that in reference [2] is discussed in Appendix I and II. The difference is in the manner in

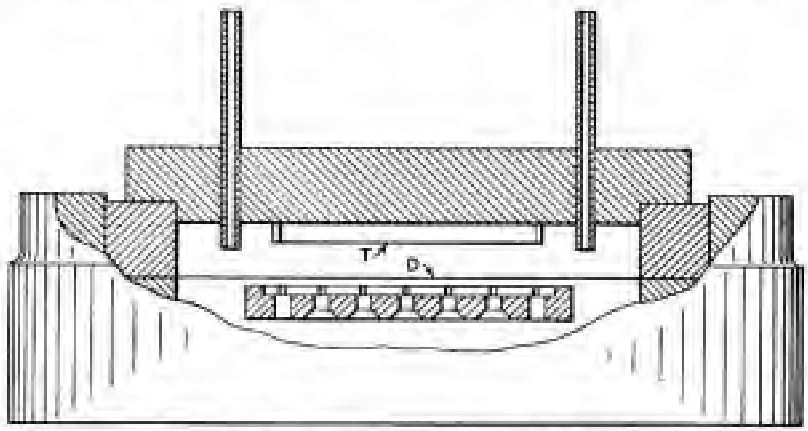

Fig. 2—Thermophone method.

which the heat conductivity of the walls is taken into account. Also a slight correction for the yielding of the diaphragm is introduced, which was superfluous with the earlier, less sensitive model. An important advantage of the thermophone method is that it is not necessary to have the heating element parallel to the diaphragm. This makes it applicable to transmitters with curved or corrugated diaphragms. In such cases it is difficult to provide the accurately parallel and narrow spacing between the diaphragm and driving or compensating electrode, required in electrostatic methods.

2. *Pistonphone.*—The pressure is generated by means of a reciprocating motor-driven rigid piston as shown in Fig. 3. The piston amplitude is computed from the dimensions and the angular velocity of the cam driving it. The motor drive makes the method suitable for relatively low frequencies, up to about 200 c.p.s.

3. *Resonating Tube.*—The pressure at the diaphragm end of the tube (see Fig. 4) is computed from a measurement of the air particle velocity at a pressure node. That velocity is obtained by observing the deflection of a Rayleigh disk, R. D., placed in the tube. The sound source R is shown as a moving coil receiver.

4. *Compensation Methods.*—The pressure in the chamber is determined by measuring the force required to prevent motion of a

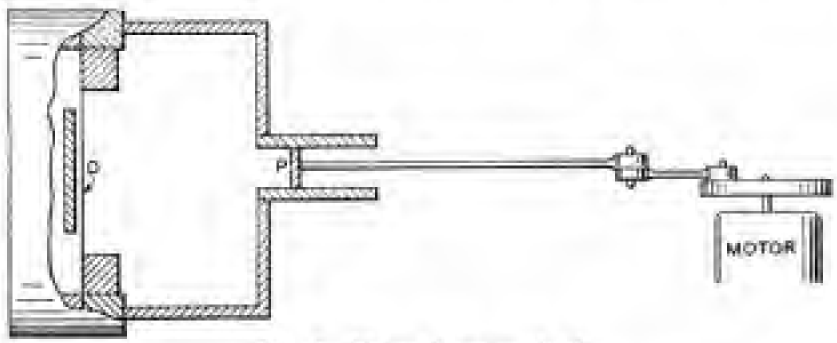

Fig. 3—Pistonphone method.

small auxiliary diaphragm D_2, Fig. 5. With the sound pressure so determined the corresponding electromotive force of the transmitter is measured. The rest condition of D_2 is indicated by absence of sound in an exploring tube communicating with the space back of D_2 or by absence of frequency variation in a high frequency circuit in which D_2 is made one plate of a condenser controlling the oscillation frequency.

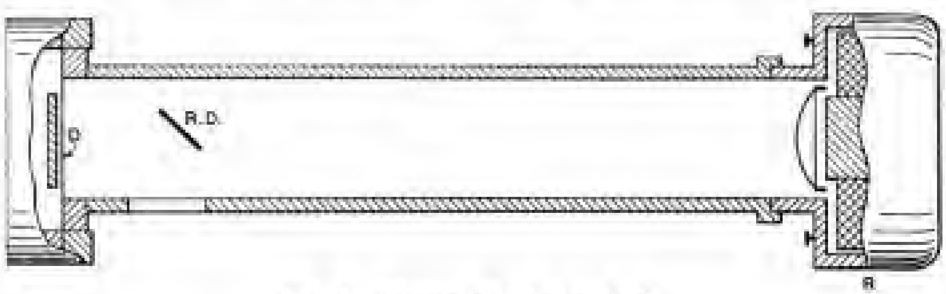

Fig. 4—Resonating tube method.

4a. *Electrodynamic Compensation for Acoustic Pressure.*—The compensating pressure is provided by sending a current of adjustable frequency, amplitude and phase through D_2 placed in a steady magnetic field.

4b. *Electrostatic Compensation for Acoustic Pressure.*—The same end is attained with a potential difference of adjustable frequency, amplitude and phase applied between D_2 and a fixed electrode parallel to it.

In particular the transmitter diaphragm and backplate may serve as D_2 and the fixed electrode. This, however, requires caution. The air gap is so small (approximately 2.5×10^{-3} cm.) that unavoidable variations in its value will in general cause appreciable variations in the value of the electric driving force over different parts of the diaphragm. The non-uniformity of the air gap is due to mechanical imperfections and to the electrostatic pull of the polarizing voltage. Furthermore, in transmitters of the type here considered, the backplate diameter is substantially smaller than that of the diaphragm, and hence the compensating electric force is not effective in a peripheral portion of the diaphragm.

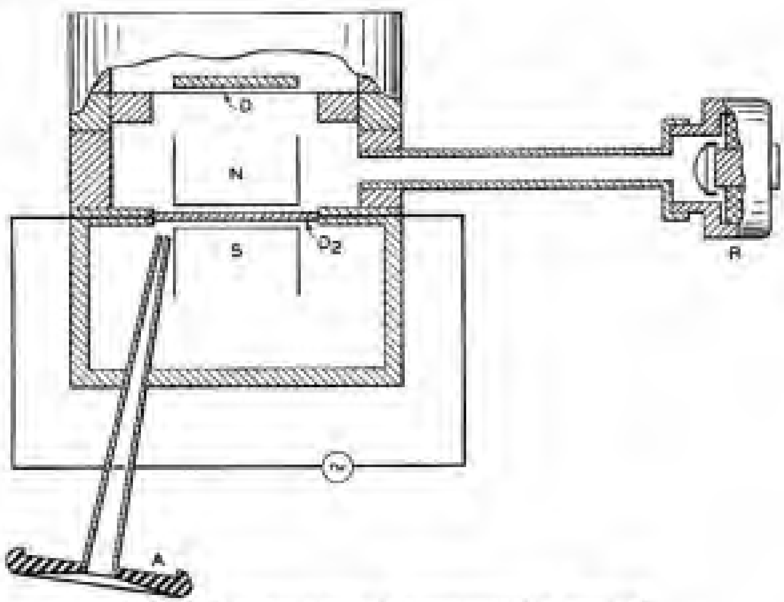

Fig. 5—Electrodynamic compensation method.

The electric force in this case is provided by inserting between the diaphragm and the backplate a steady potential difference, V_0, and a much smaller alternating potential difference, $V_1 \sin \omega t$, in series. One of the resultant force components is $\alpha V_0 V_1 \sin \omega t$ which has the same frequency as the sound source (e.g. a thermophone). The amplitude and phase of the electric force are adjusted until it balances the acoustic pressure on the diaphragm. This gives the value of the acoustic pressure, provided α is known. The compensating electric force is then removed, and the output of the transmitter due to the acoustic pressure is measured. Thus the pressure calibration is obtained. The value of α is given by a measurement of the value of V_0 required to balance a known static gas pressure established at the

face of the diaphragm. This must be done for each instrument to be calibrated.

5. *Membranephone.*—In principle this method is similar to the pistonphone. An acoustically driven membrane M (see Fig. 6) replaces the motor-driven piston. From the volume displacement, ΔV, of M the pressure on the transmitter diaphragm D is computed. The value of ΔV is given by a measurement of the alternating variation in capacitance between M and an auxiliary perforated electrode G. The range of the method is from the lowest frequencies up to those at which the linear dimensions of the chamber become comparable with the sound wave-length (λ). As with the thermophone, that upper limit can be extended through the use of hydrogen instead of air.

The computation of ΔV is given in Appendix III. It will be noted that the computation is independent of the mode in which the membrane vibrates. However, for frequencies above the first resonance of

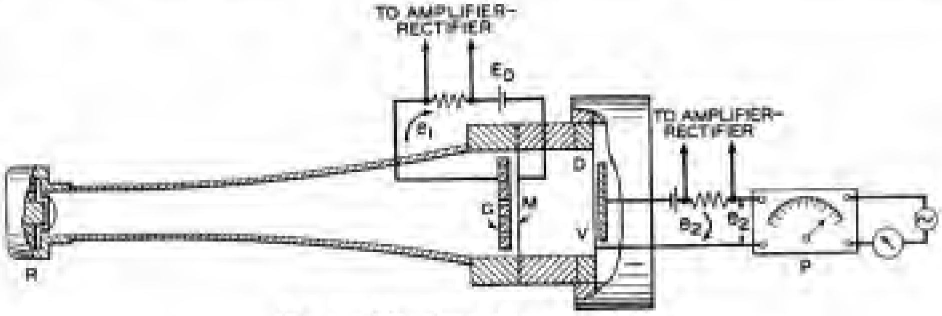

Fig. 6—Membranephone method.

the membrane the requirement as to smallness of chamber dimensions relative to λ, becomes much more stringent than in the thermophone case.

Methods Employing Electrical Drive.—Since the driving forces in this group are electric the pressure on the diaphragm is affected by the acoustic load on the front face of the diaphragm. To obtain the true pressure calibration that acoustic load must be known. Practically this is taken care of by making that load sufficiently small, rather than accurately determining its value.

6. *The Back Electrode Serving as the Driving Electrode.*—The alternating potential difference, $V_1 \sin \omega t$, is impressed in series with the steady potential V_0, see Fig. 7. This gives a driving force component $\alpha V_0 V_1 \sin \omega t$. The corresponding alternating variation in the transmitter capacitance is determined by having that capacitance control the frequency of a high frequency oscillator circuit. Absolute values are obtained by means of a static pressure calibration as in Method 4.

In this case, however, that does not give the force acting on the diaphragm unless the air impedance between the diaphragm and backplate is negligible in comparison with that of the diaphragm itself. Hence the method does not apply to the No. 394-Type Transmitter. The same consideration as to non-uniformity of the driving force over the area of the diaphragm which was mentioned in connection with Method 4*b*, applies to this case.

7. *Auxiliary Third Electrode Driving the Diaphragm.*—Here an auxiliary electrode *M* and a circular metal screen furnishes the electrostatic drive (see Fig. 8). It has nearly the same diameter as *D* and is parallel to it. The gap between *M* and *D* is about thirty times greater

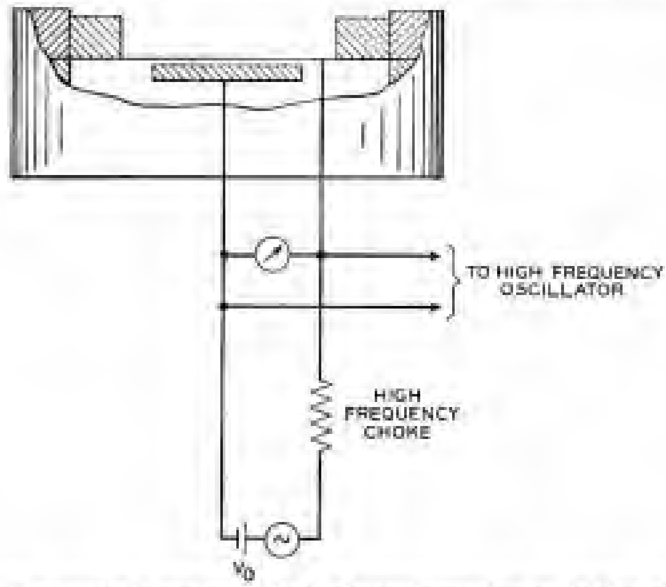

Fig. 7—Electrostatic method—Back electrode serving as driving electrode.

than between *D* and the backplate. Hence the electric force on *D* is uniform over the surface of *D*, and its absolute value can be computed with some accuracy. The calculation is given in Appendix IV. Care must be taken to avoid acoustic loading of *D* in a manner that would materially change its impedance. With this possibility guarded against, this method admits of an absolute transmitter calibration from 20 to 20,000 c.p.s. A comparison of a calibration so obtained with that given by a thermophone for the same transmitter,* is shown in Fig. 9. The two are quite independent. The discrepancy between the two up to about 6,000 c.p.s. is regarded as being within limits of experimental error. The acoustic load imposed on the diaphragm by

* This particular instrument happened to be about 4 db less efficient than the average No. 394-Type Transmitter.

the calibrating apparatus, while relatively small in either case, is not the same for both methods. At higher frequencies other factors contribute. At the highest frequencies, say above 10,000 c.p.s., the pressure on the diaphragm probably is more uniform in the present method than in Method 1.

Constant Field Calibration

For constant field calibration methods it is difficult to provide a plane progressive wave over a sufficiently large wavefront. Instead a small source in a chamber lined with highly absorbing material is used. The resultant progressive spherical wave, at sufficient distance from

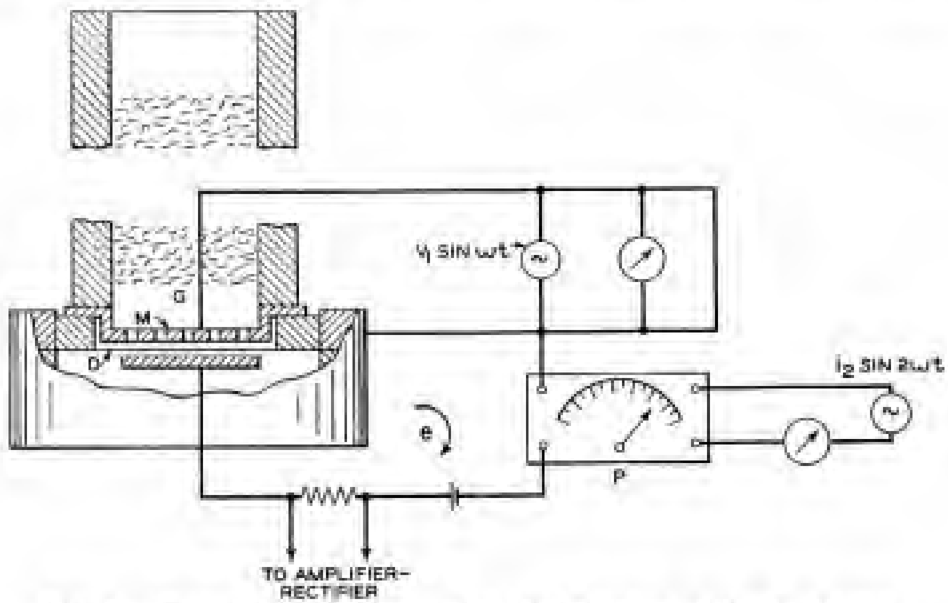

Fig. 8—Electrostatic method—auxiliary third electrode driving diaphragm.

the source, gives approximately the desired sound field. The measuring device must give the absolute value of the undistorted field intensity. We shall not consider the thermal, optical and sound radiation pressure methods possible, on account of the experimental difficulty which they present. One other absolute method is more readily available:

The Rayleigh Disc, which on certain assumptions gives the absolute value of the particle velocity in the sound wave. In the sound field presupposed for the field calibrations, the corresponding sound pressure is easily computed.[8]

Another procedure is to measure the sound pressure with the aid of a "search transmitter." This is a transmitter whose dimensions are so

small relative to the sound wave-length that its pressure calibration, as obtained say by Method 1, may be taken to coincide with its field calibration.

The normal field calibration of a No. 394-Type Transmitter is shown in Fig. 10. The contour of the particular instrument used is shown in Fig. 1*B*. It was suspended from a thin rod clamped to the metal band *B*. The measurements were made with a Rayleigh disc (0.5 cm. diameter, 2.46 second period), using the modulated sound method.[9] The transmitter was placed 32 cm. from the sound source, a 1-cm. diameter tube attached to a loud-speaking receiver. The data obtained for frequencies below 500 c.p.s., are believed to be not so reliable as the rest because of appreciable reflections from the chamber walls.

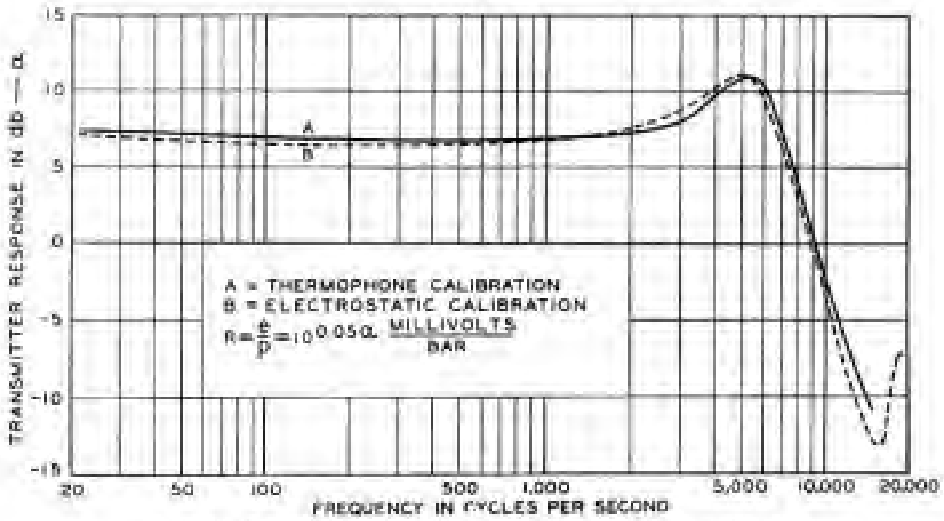

Fig. 9—Comparison of two pressure calibration methods.

For purposes of comparison, the pressure calibration (Method 7) of the same instrument is shown. At the lowest frequencies the two calibrations nearly coincide, as might be expected. At high frequencies, say from 1,000 c.p.s. upward, the divergence of the two is quite marked. It has been pointed out by several writers that the difference may be regarded as due to two effects. First,[10] as λ decreases, the transmitter tends to cause a doubling of the pressure in front of it as would a rigid wall. Second,[11] the recess in front of the diaphragm (Fig. 1) introduces a broad resonance which has its maximum approximately at 3,500 c.p.s. An estimate of this effect is given in Appendix V.

The observed differences between the field and pressure calibrations, from 500 to 8,000 c.p.s. are in fair agreement with those computed for

the two effects given above. The computations are based on assumptions as to the transmitter contour which are quite removed from the actual case. Thus for the first effect it has been suggested that the transmitter may be replaced by an "equivalent" rigid sphere of equal

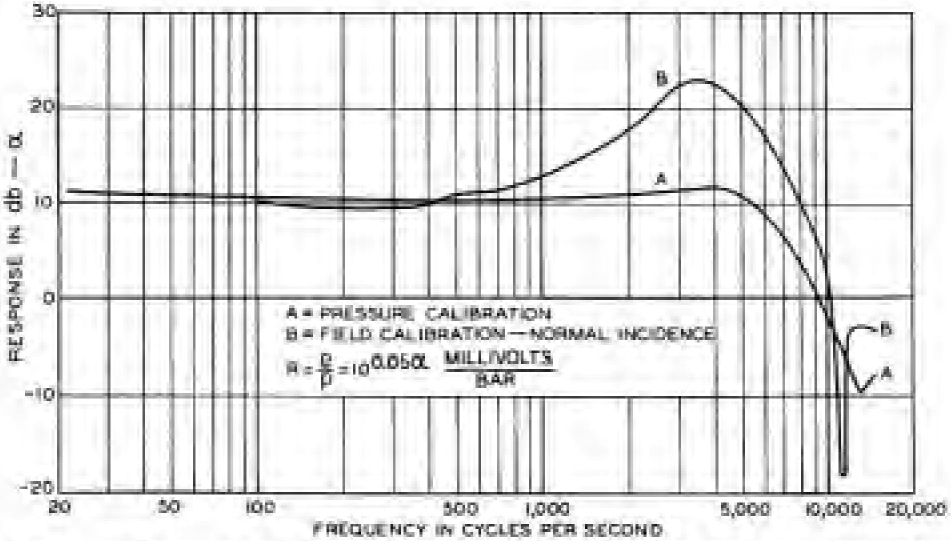

Fig. 10*A*—Pressure and field calibrations of No. 394-type condenser transmitter.

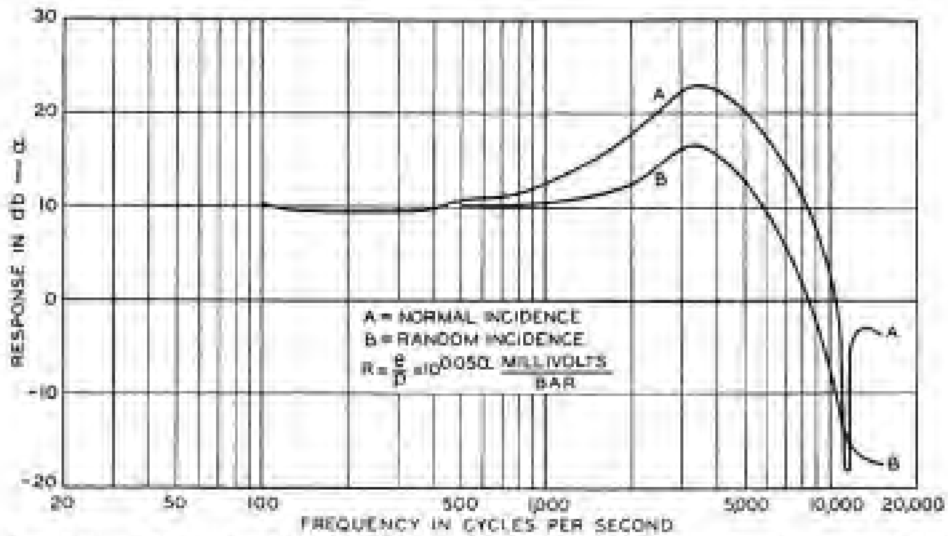

Fig. 10*B*—Field calibrations of No. 394-type condenser transmitter for normal and random incidence.

volume [12] or of equal diameter.[13] The data in Fig. 10*A* are best fitted by assuming a sphere of 9 cm. diameter, i.e., a diameter even larger than that of the transmitter. For the second effect the assumption is made that the face of the transmitter acts as an infinite wall, and that

the air particles in the recess aperture all move in phase and normally to the diaphragm.

At still higher frequencies the doubled pressure effect largely persists and superposed on it are a number of rather complicated diffraction effects. These involve radial wave propagation across the diaphragm recess while the above two effects are due to normal plane waves. The marked dip at 11,200 c.p.s. corresponds to a sound wave-length such that

$$\sqrt{\left(\frac{1}{2}PQ\right)^2 + (PA)^2} - PA = \frac{1}{2}\lambda$$

(see Fig. 1*A*).

So far normal incidence of the sound wave has been assumed. For other directions of arrival, substantially different field calibrations are obtained. Since the transmitter is symmetrical about any diaphragm diameter, the effect of direction may be given in terms of the azimuth angle of incidence. A set of azimuth curves for various frequencies are given in Fig. 11, all expressed relative to the normal field calibration. In general, the higher the frequency the greater the effect of azimuth. For a large range of angles that effect is as great as or greater than the difference between the pressure and the normal field calibrations. It is interesting to note that the anomalous azimuth curve at 11,200 c.p.s. corresponds to a pronounced dip at that frequency in the normal field curve.

Relation of Field Calibration to Actual Transmitter Performance

We now consider the bearing of field calibrations upon the response of the No. 394-Type Transmitter under one or two conditions of actual use.

First, consider the case of a person speaking directly toward the diaphragm. The normal field calibration approximately applies, provided the distance is not great enough for reflected waves to be comparable with the direct wave and the distance is not so small that the transmitter reacts back on the source (the voice), or that pronounced standing waves are set up between the transmitter and the head. Outdoors and in a well damped room distances ranging say from 6 inches to 3 feet are likely to be within the above limits for the important voice frequencies.

On the other hand, for much of indoor work the distances from the microphone to the source and to the several reflecting surfaces are such that waves reaching the microphone by reflections are comparable with and often predominate over the direct sound. Besides, the microphone often is so placed that the direct sound strikes it more

nearly at a 45-degree or 60-degree angle rather than normally. In a 29-foot × 29-foot × 13-foot room having a reverberation time of 1

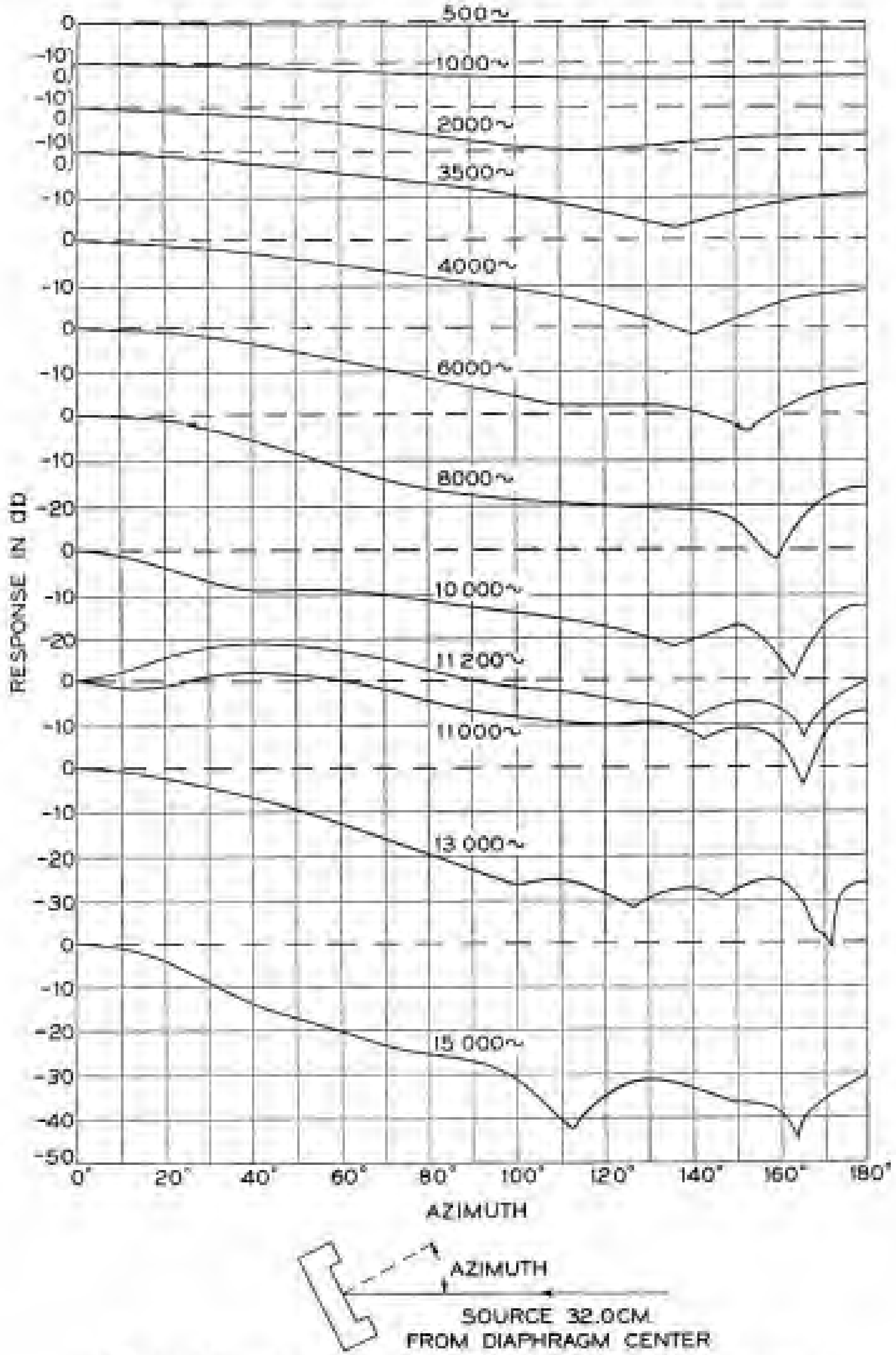

Fig. 11—Azimuth response of No. 394-type condenser transmitter.

second, the reflected waves reaching the microphone at 12 feet from a small source contribute much more to the microphone output than does the direct sound. To illustrate the effect of these reflections, the curve (*b*) in Fig. 10*B* has been plotted. It is based on the data of Fig. 10 and Fig. 11, and assumes that the transmitter is acted upon by progressive plane waves arriving with equal intensity from all directions in space. Their phases are taken to have random distribution. At any one frequency the response of the transmitter is then proportional to

$$\sqrt{\int_0^{\Pi} [A(\theta)]^2 \cdot \sin \theta \cdot d\theta},$$

where $A(^\theta)$ is the azimuth factor taken from Fig. 11. The result is seen to be intermediate between the pressure and the normal field calibrations, for frequencies up to about 8,000 c.p.s. Under these circumstances it is immaterial which way the diaphragm faces, but this holds only for sustained sounds. For sounds of short duration, the peak amplitudes in the microphone output often are of particular interest. They will be more nearly given by that single field curve corresponding to the azimuth with respect to the sound source in which the transmitter happens to be.

The above discussion of directional effects is simplified by the fact that the No. 394-Type Transmitter is symmetrical about any diaphragm diameter. Hence a single parameter—azimuth angle—is sufficient. The amplifier mounting cases usually employed destroy that symmetry. The directional effect becomes much more complicated since it involves two parameters, e.g. two direction cosines of the diaphragm axis. It has been suggested [12] that this complication can be done away with by placing the transmitter and its amplifier case in a rigid hollow sphere, only the transmitter front being exposed. If the front contour of the instrument be designed closely to conform to the rest of the sphere, and if the diaphragm subtend a sufficiently small angle at the center of the sphere, the directional effect can be computed.[14]

The simplest directional properties, i.e. uniform response for all directions of incidence, require a transmitter whose linear dimensions are small (say $< \frac{1}{4}\lambda$) relative to the shortest sound wave-length to be picked up. For a frequency range extending to 10,000 c.p.s., this means a transmitter less than 0.85 cm. in diameter. In general such restriction on the permissible size adds to the difficulties of construction and operation of the instrument. It is not intended to imply that non-

directivity of the transmitter is always desirable for pickup systems of highest quality.

A complete description of the performance of the microphone as an electro-acoustic converter is extremely complex. It involves the microphone, the sound source, their relative positions, and the surrounding acoustic configuration. Furthermore, it is limited to sound sustained long enough to allow the reflection pattern to attain a steady state. Therefore, in order to obtain a reasonably simple and useful statement of the transmitter response, the field calibration is made under the ideal acoustic conditions stated in part *A*. Even then the field calibration (including, of course, the azimuth measurements) is far more difficult and laborious than the corresponding pressure calibration. For some important purposes the pressure calibration is sufficient, even though the transmitter be intended for use in an "open" sound field. An instance is the specification and comparison of instruments having similar contours. The difference between the field and pressure calibrations, once determined for an individual instrument, applies to all others. That is, provided the acoustic impedances of their diaphragms are not too widely different, which usually is the case. Therefore the response of any instrument, as a function of frequency, age, barometer pressure, temperature, etc., is given by the pressure calibration. The thermophone method (Method 1) is particularly suitable for rapid and reproducible determinations of the pressure calibration. That is the method employed for the specification of No. 394-Type Transmitters, and of others having similar contours, in the Master Reference Systems [18] for Telephone Transmission in Europe and in this country.

I am indebted to Messrs. R. T. Jenkins, H. T. O'Neil and E. M. Little of Bell Telephone Laboratories for much of the material used in this paper.

Appendix I

The pressure generated by the thermophone is slightly reduced by the heat conductivity of the chamber walls. That conductivity is so great as compared with that of the gas, that zero temperature variation at the walls may be taken as one of the boundary conditions of the problem. This results in a solution nearly identical with that of eq. (7), p. 336, in the original derivation.[2] The correction factor given there on p. 340, which takes care of the wall conductivity, is now found to be more nearly unity. The difference between the two solutions is shown in Fig. 12 for a special case typical of condenser transmitter calibrations. As might be expected, it is greater the lower the frequency.

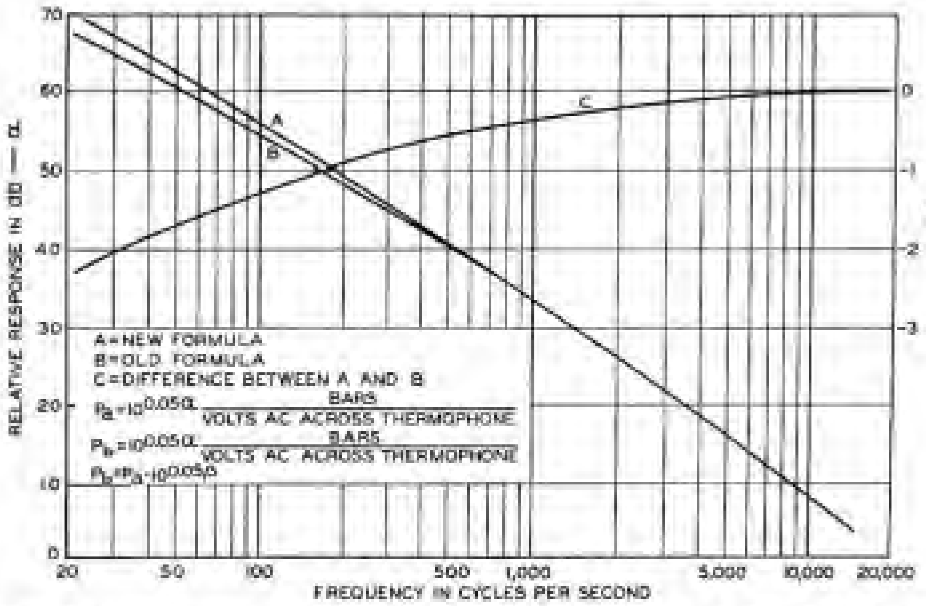

Fig. 12—Pressure generated by a thermophone in a transmitter calibration chamber.

Appendix II

In the thermophone theory the walls of the chamber were treated as being rigid. Actually the transmitter diaphragm presents a small but finite admittance in shunt with the elastic admittance of the gas in the chamber. The correction factor M due to this, is approximately

$$M = \frac{1}{\sqrt{1 + \frac{(\gamma p_0 v)^2}{V_0} + 2\frac{\gamma p_0 v}{V_0} \cdot \cos\theta}},$$

where

$$\gamma = 1.4 = \frac{C_p}{C_v},$$

assuming adiabatic conditions

$p_0 = 10^6$ bars atmospheric pressure,
$V_0 =$ volume of thermophone chamber,
$v =$ volume displacement of diaphragm per bar,
$\theta =$ phase angle of above displacement with respect to the pressure on the diaphragm.

At low frequencies $\cos\theta$ may be taken as nearly unity, and v can be approximately computed as below

$$v = \tfrac{1}{3}\Pi a_1^2 y,$$

$$y = \frac{\Delta C}{C}(h - y_1)\left[\frac{1 - \frac{1}{2}\frac{a_2^2}{a_1^2}\cdot\frac{y_1}{h - y_1}}{1 - \frac{1}{2}\frac{a_2^2}{a_1^2}\left(1 + \frac{2y_1}{h}\right) + \frac{1}{3}\frac{a_2^4}{a_1^4}\cdot\frac{2y_1}{h - y_1}}\right],$$

$$\frac{\Delta C}{C} = \frac{C_3}{C_2}\cdot\frac{e_1}{E_0}, \qquad \text{and} \qquad y_1 = \frac{h\left(\frac{C_2}{C_1} - 1\right)}{1 - \frac{1}{2}\frac{a_2^2}{a_1^2}},$$

where h = separation between diaphragm and back plate without polarizing voltage.
- C_1 = capacity between diaphragm and back plate without polarizing voltage.
- C_2 = above capacity in presence of polarizing voltage.
- C_3 = total transmitter capacity, with polarizing voltage.
- E_0 = polarizing voltage.
- e_1 = transmitter e.m.f. per bar, uncorrected for yielding of diaphragm.
- a_1 = diaphragm radius; a_2 = back plate radius.

For the 394-Type Transmitter, up to about 2,500 c.p.s., M is nearly 0.92. Above that the correction decreases owing to decreasing cos θ, and becomes negligible at 5,000 c.p.s. For still higher frequencies the correction becomes negative but remains small due to the increasing diaphragm impedance.

Appendix III

Schematically the membrane phone is shown in Fig. 6. D is the diaphragm of the transmitter to be calibrated; M, a stretched membrane acoustically driven from the receiver R; G, a perforated plate. Let V = volume between D and M; y_0 = normal separation between G and M; C_0 = normal capacitance between G and M.

Then, if $y_0[1 + K(S)\cdot \sin \omega t]$ represents the GM separation when M is driven by R, the resultant capacitance variation is:

$$\Delta C = \sin \omega t\cdot\frac{1}{4\Pi y_0}\cdot\int\frac{K(S)}{1 + K(S)\sin \omega t}\cdot dS$$

and

$$\Delta V = \sin \omega t\cdot y_0\int K(S)\cdot dS,$$

the integration extending over the entire area of M.

Taking $K(S) << 1$, but without restrictions on the variation of $K(S)$ over the surface of M,

$$\Delta V = 4\Pi y_0^2 \cdot \Delta C_0.$$

Hence the transmitter sensitivity is given by

$$R = \frac{e_2}{p} = \frac{e_2 V E_0}{\gamma p_0 \cdot 4\Pi y_0^2 C_0 \cdot e_1} \text{ volts/bar.}$$

The above presupposes: (1) $V/S << \lambda$, $\sqrt{S} << \lambda$; (2) acoustic admittance of D is very small compared with that of V; (3) adiabatic compression. If necessary, corrections for deviations from (2) can be made in accordance with Appendix II. The correction for (3) is found to reduce the pressure in the ratio

$$R' = R \cdot \frac{1}{1 + (\gamma - 1) \cdot \dfrac{\tanh \beta a}{\beta a}},$$

where

$$\beta = (1 + i)\sqrt{\frac{\rho \omega C_p}{2K}},$$

when C = specific heat at instant pressure,
K = thermal conductivity of the gas,
ρ = density,
$\gamma = \dfrac{C_p}{C_v}$.

The upper frequency limit imposed by condition (1) can be raised by filling V with hydrogen. For the No. 394-Type Transmitter, and with R a No. 555-W Western Electric Receiver, an air-gap $y_0 = 0.075$ cm. corresponds to easily measurable values of e_1 and e_2. M was a 0.001 inch duralumin diaphragm, stretched to 5,000 c.p.s. resonance frequency. It was found that the upper frequency limit of the method is determined by M breaking up when vibrating in one of its higher natural modes. This tends to produce a non-uniform pressure on D, and the above condition must be met much more perfectly than in the thermophone case.

Appendix IV

The particular electrostatic calibration described below, employs a separate driving electrode and a sinusoidal driving voltage which produces a sinusoidal driving force of double frequency. The latter has the advantage of adding frequency selectivity to shielding as the

means for keeping the relatively large driving voltage out of the transmitter output circuit.

In terms of Fig. 8 the sensitivity of the transmitter is given by

$$R = \frac{e}{p} \text{ volts/bar}, \quad e = i_a r_a \cdot 10^{-0.05\alpha}, \quad p = \frac{V^2}{9 \times 10^4 \times 8\sqrt{2} \cdot \Pi h^2},$$

where $V\sqrt{2} = V_1$, measured in volts, $i_a\sqrt{2} = i_1$, h = separation between M and D. The e.m.f. e is measured by means of the potential attenuator P, carrying a known current i_a, and having an input resistance r_a. At any one frequency two quantities must be measured: V, say with an electrostatic voltmeter, and α, the setting of the attenuator in decibels. The current i_a must be known but can readily be kept constant at all frequencies if a heterodyne oscillator be used as the source.

Two corrections must be applied. First, the auxiliary electrode is perforated. Hence not all of its area is electrostatically effective. Second, p in the above is the electrostatic force per unit area, rather than the acoustic pressure on the diaphragm. The two are different, in general, because of the acoustic load (Z_d) on the front face of the diaphragm. The value of Z_d is affected by form of C, the auxiliary electrode, and by the acoustic impedance beyond it in the chamber G.

It is best to have Z_d as small and as free from reactance as possible. This is accomplished by using stretched fine metal gauze. Copper gauze, 300-inch mesh, is quite good. It terminates in the tube TT, ¼-inch iron wall, which is filled with several layers of loose cotton batting and hairfelt. The effectiveness of the arrangement was judged by the fact that altering the size of G did not appreciably affect the calibration.

While the screen electrode provides a practically uniform electrostatic pressure over the surface of D, it is rather complicated to compute the effective absolute values of h and of the electrostatic area. This is more easily done by comparing it at low frequencies (say at 100 c.p.s.) with a steel plate electrode in which the perforations take up about 12 per cent of the total area. The surface facing D is carefully machined so that h is uniform and known within less than $\pm$ 2 per cent. This is for absolute values of h in the range 0.075–0.080 cm. The acoustic load which this electrode imposes on D, with G removed, is negligible at low frequencies. A lower limit on the electrostatic correction for the perforations is made by adapting the calculation given by Maxwell ("El. Mag.," 3d ed.) for rectangular grooves in one plate of a parallel plate condenser. The above value of R is corrected to

$$R' = R \cdot \frac{1}{1 - \frac{S_1}{S} \cdot \frac{g}{h+g} - \frac{S_1}{S} \cdot \frac{gh}{(h+g)2}},$$

when

$$g = \frac{\sqrt{S_1} \cdot \log_e 2}{\Pi}, \qquad S_1 = \text{area of perforation}, \qquad S = \text{total area}.$$

An upper limit on the above correction is given by:

$$R' = R \cdot \frac{1}{1 - \frac{S_1}{S}}.$$

The R' actually used was the mean of the above two values. The value of R obtained with the screen electrode is shifted up or down to make it coincide with R' given by the perforated electrode, at 100 c.p.s.

Appendix V

For frequencies below about 5,000 c.p.s. the difference between the pressure and normal field calibrations is mainly due to two effects: (1) reflection from the transmitter face and from the diaphragm; (2) air resonance caused by the recess in front of the diaphragm.

Consider Fig. 1*A*. Assume that in the circular aperture PQ, the air particles are all moving in phase and parallel to AP. Then we may treat PQ as a rigid massless piston in the wall RS. If RS/λ is large enough, the pressure on PQ held motionless will be double that of the field pressure. The motional impedance of PQ imposed by the air above PQ is given by Rayleigh (Sound, vol. II, § 302). Per unit area it is

$$Z_1 = \rho C(a + ib),$$

where

$$a = 1 - \frac{J_1(2kR)}{kR}; \quad b = \frac{\omega\rho\Pi}{2k^2} K_1(2kR); \quad k = \frac{2\Pi}{\lambda}; \quad 2R = PQ.$$

Let R_F/R_P represent the ratio of " field " to " pressure " calibration. Using the expression for plane wave propagation in a tube (e.g. Crandall, Theory of Vibrating Systems and Sound, p. 99) we have at once:

$$\frac{R_F}{R_P} = 2 \cdot \frac{1}{[\cos kl + i(a+ib) \cdot \sin kl] + \frac{\rho C}{Z_A}[(a+ib)\cos kl + i \sin kl]},$$

where Z_A is the equivalent impedance per unit area of the transmitter diaphragm, and $l = AP$. On substituting numerical values, R_F/R_P is

found to have a maximum value of nearly 3.3 at $\omega/2\Pi = 3500$ c.p.s. This means that the air resonance adds a factor of 1.65 to the ordinary doubling of pressure caused by a plane wall. A substantially similar calculation has been given by W. West.[13]

The observed R_E/R_F is a maximum at 3,500 c.p.s. but its value is somewhat larger—nearly 3.65.

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